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14. ABSTRACT
To develop techniques required to produce and store atoms made entirely of anti-matter. Anti-matter provides high-density energy storage that far outstrips even nuclear materials. Potential applications for anti-matter include rocketry and explosives. In the last grant period, a new positron accumulator was developed. Follow-up research is needed to develop the techniques to transfer the substantially increased number of positrons from the accumulator to the anti-hydrogen apparatus. In the last grant period, a new method for loading electrons needed to cool antiprotons was developed. This new method is more robust, faster, and easily controllable. Follow-up research is needed to test this new method with anti-protons. Also, the PI has proposed to try two different magnetic traps to trap the anti-hydrogen as it is formed. Finally, the goal of precision 1s-2s spectroscopy will be addressed via laser cooling of anti-hydrogen.

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A. Project Summary and Statement of Objectives

AFOSR support launched and continues to sustain this unique antimatter research study of antiprotons and antihydrogen, the annihilation of which produce the maximum energy per unit mass. The practical goal is to develop the unusual techniques required to produce and store atoms made entirely of antimatter, given that the slightest encounter with ordinary matter will cause them to turn all their mass into energy as they annihilate. The scientific goal, which gives this program a highly leveraged access to the world's unique and extremely limited supply of antiprotons, is to use laser spectroscopy to compare the properties of matter and antimatter atoms to extremely high precision – promising to be the highest precision test of the fundamental CPT theorem with leptons and baryons.

The first observations of slow antihydrogen atoms several years ago were widely celebrated and reported, in venues ranging from the scientific Physical Review Letters, Nature, Science, and Physics Today, to the popular science reports in CNN, most major newspapers, and most other news outlets. The American Institute of Physics even selected the production and observation of cold antihydrogen as one of the two top physics stories of the year.

Much progress has been made since. Most recently, during the nearly completed grant period, a new ATRAP-II apparatus was commissioned. The goal was much larger and colder plasmas of positrons and antiprotons for antihydrogen production, along with room for magnetic traps and laser diagnostics. It was a huge effort but this apparatus is now operating well. Notable advances realized already include:

1. Many orders of magnitude more positrons are now available for antihydrogen production, as needed for better collisional cooling of $\overline{\mathrm{H}}$ atoms that are formed.
2. Many more antiprotons are now available within a 1 Tesla magnetic field, the highest field compatible with the confinement of positrons, antiprotons and antihydrogen atoms in the same volume. The $\overline{\mathrm{H}}$ production rate goes as the number of antiprotons.
3. A quadrupole Ioffe-Penning trap is installed and operating within the cryogenic environment. Penning traps hold the positrons and antiprotons from which $\overline{\mathrm{H}}$ atoms are produced. The Ioffe trap should capture and store sufficiently cold antihydrogen atoms.
4. The accumulation of antiprotons within a quadrupole Ioffe trap field was demonstrated. Losses that some had predicted would prevent antihydrogen production did not take place.
5. The first demonstration of antihydrogen atoms produced within the Penning-Ioffe trap field took place.
6. Apparatus to lower electron and positron plasma temperatures to 1.2 K electrons was demonstrated. Plasmas of this temperature should be an extremely important step towards producing $\overline{\mathrm{H}}$ atoms that are cold enough to be trapped.

Scientific publications report the scientific progress. Other indicators show the impact and widespread appreciation of this work. In recent years the PI was invited to present as many as 50/year scientific and popular scientific lectures. Numerous students and postdocs trained in this program now lead their own research efforts in national labs and in universities. Patented solenoid designs are available commercially for ICR, NMR and MRI imaging, and trap designs are being used in devices that analyze pharmaceuticals and chemical compounds.

This research program is highly leveraged, and is the sole US-led research effort with extremely low energy antiprotons. It takes place at the only low energy storage ring in the world – a unique and substantial facility built at the world's leading particle physics laboratory (CERN). The storage ring facility is maintained, operated and supported by CERN and its personal. In fact, this substantial facility was specially built so that the antihydrogen research program proposed by the PI could be carried out, a vision made possible by the low energy antiproton techniques pioneered by this AFOSR supported research program.

The recent progress bodes well for the two immediate challenges of current antihydrogen research. The first is to obtain the slowest possible antihydrogen atoms – slow enough to be trapped in a magnetic trap. The second is to de-excite antihydrogen atoms through a chaotic orbit region and down to their internal ground state. Both goals require the apparatus that produces larger and colder positron and antiproton plasmas that has now been realized.

Very promising initial demonstrations must now become robust and reproducible methods that are optimized and understood. Trapped antihydrogen are the goal though this likely will require the completion of a second generation Ioffe trap that is currently under construction. The new trap is designed to be turned off in ms rather than in minutes for much more sensitive detection of trapped antihydrogen. The new trap is also designed to allow the order of the Ioffe field to be changed. The possibility of producing sub-K temperature plasmas is being explored, and new laser tools needed to cool and probe the unique atoms made entirely of antimatter are being developed.

The Production and Study of Cold Antiprotons and Antihydrogen

Contents

1. Recent Accomplishments Point the Way Forward

Considerable progress toward the precise laser spectroscopy of antihydrogen was made during the last couple of years. Some of the significant steps are listed. Often the step is significant because it opens the way to an experimental path that we should clearly pursue during the next grant period. If so, the resulting objective for the next grant period is also specified.

Two review papers by the PI summarize the progress that was made before what is described here. The first is entitled "Comparing the Antiproton and Proton, and Opening the Way to Cold Antihydrogen" [1]. The second is entitled "Atoms Made Entirely of Antimatter: Two Methods Produce Slow Antihydrogen" [2].

a. An Encouraging Theoretical Interpretation of Measured $\overline{\mathrm{H}}$ Velocities – Phys. Rev. Lett. 97, 143401 (2006).

Before the current grant period began we measured velocities for detected $\overline{\mathrm{H}}$ atoms that were much higher than average thermal velocities for 4.2 K (the temperature of the trap apparatus) [3]. These velocities were much too high for there to be any chance of capturing $\overline{\mathrm{H}}$ atoms in even the deepest magnetic trap that one could realistically expect to construct and operate.

However, our subsequent theoretical study suggested an alternate interpretation to us [4]. The calculation indicates that cold antihydrogen could actually being produced initially, just as we originally expected. The atoms that travel to our detector, however, pass through higher energy, trapped antiprotons as they oscillate back and forth in the side wells of the nested Penning trap. With a surprisingly high efficiency, the e^+ on a produced $\overline{\mathrm{H}}$ atom is able to jump over to a higher speed $\overline{\mathrm{p}}$. The higher speed $\overline{\mathrm{H}}$ is then what we detect because it makes it more readily to our detection region. The dashed line in Fig. 1, from the simulation, agrees as well with the data (open circles in the figure) as does the monoenergetic higher energy distribution assumed in the original interpretation.

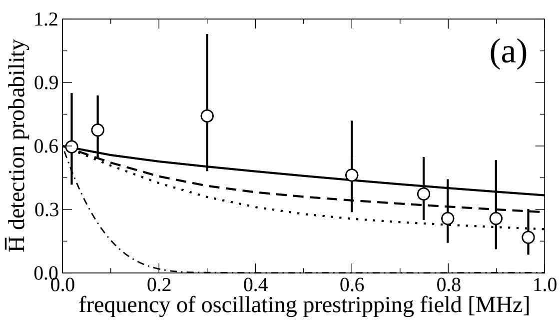

Figure 1: Theoretical simulations, which include a surprisingly large probability for a e^+ in a slow $\overline{\mathrm{H}}$ atom to jump to a higher speed $\overline{\mathrm{p}}$ as it travels to our $\overline{\mathrm{H}}$ detector, agree with our $\overline{\mathrm{H}}$ velocity measurements as well as did the earlier assumption of monoenergetic, high speed $\overline{\mathrm{H}}$ atoms.

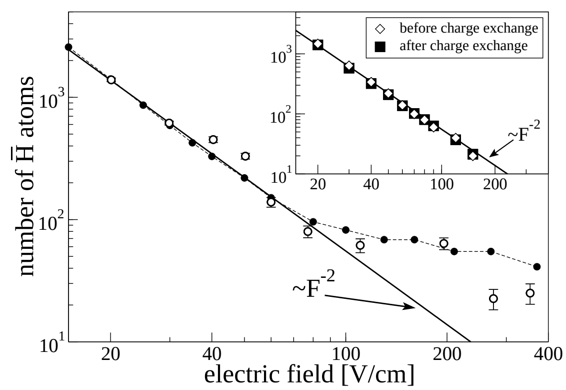

Figure 2: Theoretical simulations (solid dots) for the first time reproduce the observed field ionization spectrum for produced $\overline{\mathrm{H}}$ atoms (large open circles), signifying a substantial advance in our understanding of $\overline{\mathrm{H}}$ formation.

For the next grant period, the message of this recent theory work is that cold $\overline{\mathrm{H}}$ atoms are being produced, even though the atoms that we have detected so far have subsequently acquired a higher velocity because of the charge exchange. This encouraging message suggests that we should attempt to trap $\overline{\mathrm{H}}$ atoms since some of these atoms could be cold enough to trap if the energy of the interaction of the antiprotons and positrons in the nested Penning trap is carefully controlled. Our first generation Ioffe trap is currently ready for such studies, and an improved second generation Ioffe trap is under construction. There is yet no experimental answer to whether $\overline{\mathrm{H}}$ trapping will be possible possible before the atoms decay into their ground state, but excited atoms may be more easily trapped owing to their large moments. The best scenario would be to have some of the $\overline{\mathrm{H}}$ atoms remain trapped as they decay into their ground states.

b. First Theoretical Calculation of the $\overline{\mathrm{H}}$ Field Ionization Spectrum – Phys. Rev. Lett. 97, 143401 (2006).

Before the current grant period we had measured the field ionization spectrum of the $\overline{\mathrm{H}}$ atoms produced during positron cooling of antiprotons [2], but this spectrum was not understood. The spectrum revealed the distribution of atom sizes that were produced. However, there was no understanding of how this distribution arose.

The second of two messages in the theoretical PRL [4] is that we have been able to calculate the hydrogen field ionization spectrum that is observed. The measured spectrum is the open circles with error bars in Fig. 2. The solid points are the results of our calculation. There is good agreement in the power law region of low electric field. There is also good agreement for larger electric fields, which correspond to more tightly bound atoms. This good agreement is very exciting insofar as the internal $\overline{\mathrm{H}}$ atoms have chaotic internal orbits in this region.

For the next grant period, this encourages us to believe the indication in the measured and calculated spectra that suggest that $\overline{\mathrm{H}}$ atoms that are more deeply bound than first seemed possible could well be being produced. The consequence is that it seems reasonable to look for trapped antihydrogen atoms in the hope that at least a few of those produced are deeply bound enough to be trapped.

c. Density and Geometry of Single Component Plasmas – Phys. Lett. B 650, 119 (2007).

The density and geometry of antiprotons and positron plasmas in realistic trapping potentials are required to understand and optimize antihydrogen formation. For the first time we have been able to compare an aperture method and a quadrupole oscillation frequency method for characterizing such plasmas, using trapped electrons [5]. Both methods are used in a way that avoids the usual assumption that the plasmas are spheroidal. The measurements showed clearly that the two measurement method did not agree if spheroidal plasmas were assumed. However, we realized good agreement between the two methods when we relied upon calculation of more realistic plasmas shapes, illustrating the possibility to accurately determine plasma densities and geometries within non-idealized, realistic trapping potentials.

For the next grant period we will increasing rely upon such measurements to determine the density and geometry of our plasmas. Already we used what we learned to reach the initial conclusion that, under the right circumstances, that we could attain 1.2 K electron (and presumably positron) plasmas. This will be a major focus of the next grant period, enabling us to carefully optimize the positron plasmas for the coldest possible production of antihydrogen atoms [6].

d. Commissioning of a Completely New ATRAP-II Apparatus – (major apparatus paper being prepared).

An entirely new apparatus, represented in Figs. 3 and 4, was commissioned during the last grant period. This was a huge effort for our small team, and it is now starting to pay substantial dividends. The large ATRAP-II apparatus was required for three reasons:

1. More volume was required to permit the accumulation of larger antimatter plasmas, as needed so that an excited $\overline{\mathrm{H}}$ atom that is formed has the opportunity to cool as it collides with many more cold positrons before it escapes the plasma. Many collisions are required to de-excite the atoms to states near enough to the ground state that radiation can dominate the de-excitation, yielding ground state atoms.
2. More volume was required to allow the use of an increasing number of laser diagnostics, to give access for lasers for $\overline{\mathrm{H}}$ cooling and spectroscopy.
3. More volume was required to allow us to add magnetic traps for the eventual trapping of antihydrogen atoms.

The new apparatus is now fully operating, though we have much to learn and optimize, of course. The apparatus will likely profit from many small improvements as we learn.

e. Extremely Large Increase in the Number of Available Positrons.

We needed many more positrons to better cool the $\overline{\mathrm{H}}$ atoms that we form within the trapped positron plasma. We thus built bigger Penning traps to make this possible. To fill the much larger positron and antiproton interaction volumes, we designed and built a new positron accumulator (Fig. 4). It involves a strong radioactive source, and a series of large-diameter, gas-filled Penning traps [7]. This effort is led by a professor at York University who not so long ago was a postdoc in our group, supported by this research

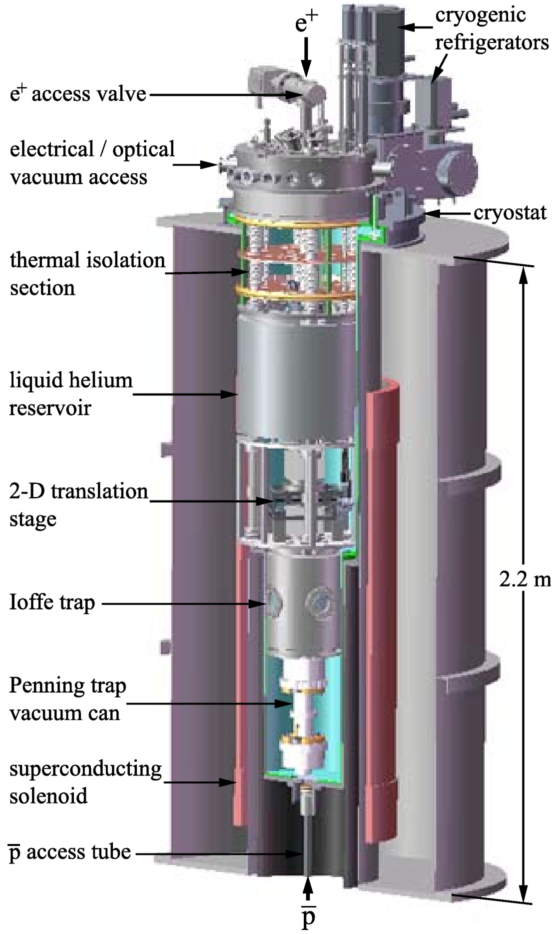

Figure 3: New ATRAP-II antihydrogen apparatus is much larger than the apparatus ATRAP first used to produce antihydrogen atoms. The large volume makes room for more extended plasmas in larger Penning traps, substantial laser access, and magnetic traps.

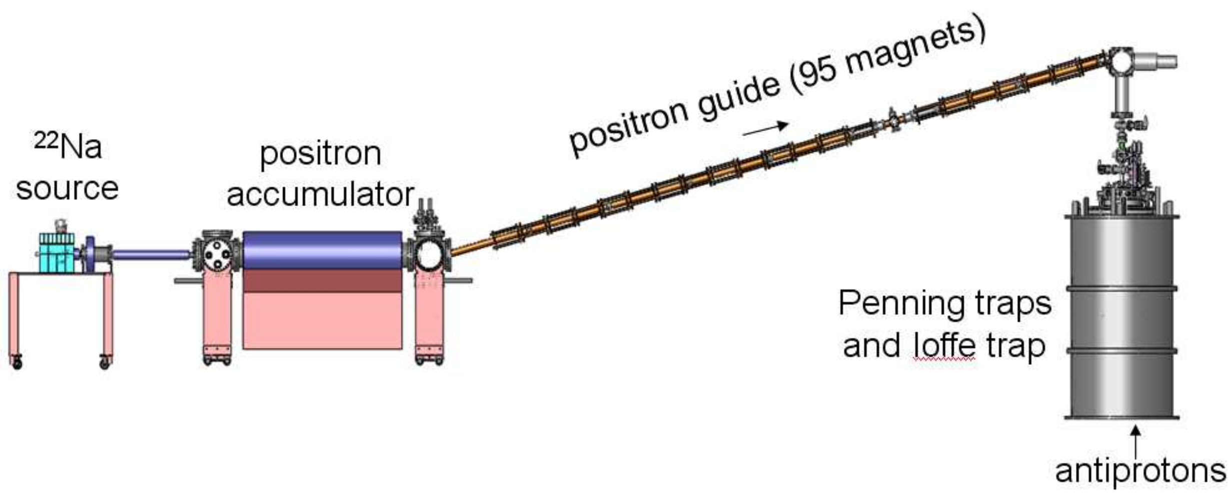

Figure 4: Substantial new ATRAP-II positron accumulator of greatly increases the number of positron available for antihydrogen production. They are transported 8 meters to be captured in the cold trap with antiprotons for $\overline{\mathrm{H}}$ production, within the apparatus of the previous figure.

program. Our role was to develop the interface of the positron guide and the antihydrogen trap, and to develop the methods needed to capture pulses of positrons that are sent though the positron guide.

Instead of acquiring several million positron over night, we now load at least 10 million positrons every 100 seconds. This allows us to typically use 60 to 100 million positrons for each antihydrogen production trial, rather than the 1 million or less positrons typically available in our previous apparatus.

During the next grant period we will continue to profit from the much larger positron plasmas, and hope to slowly increase the number of positrons even further. As will be discussed presently, the major focus will be upon realizing the lowest possible positron temperature, and upon cooling the positrons in the shortest possible time.

f. Five Times More Antiprotons are now Available at 1 Tesla

The use of a Ioffe trap required that we lower the magnetic field in our Penning trap to 1 Tesla. A higher bias field serious reduced the strength (i.e. depth) of the Ioffe trap. The number of antiprotons that we captured per shot from the AD went down substantially as we reduced the field from 3 to 1 Tesla. We thus installed an additional solenoid to boost the magnetic field in the capture region of our trap. This worked extremely well, as expected, boosting the number of cooled antiprotons per pulse of antiprotons from the AD by about a factor of five – a very significant improvement.

For the next grant period we will profit significantly from the five-fold increase in the number of antiprotons, since the number of produced $\overline{\mathrm{H}}$ atoms is proportional to the number of antiprotons. We may be able to optimize the number of antiprotons that are transferred from the high field capture region into the 1 Tesla volume at the center of the magnetic trap region, but this is not certain.

g. Single-Component Plasma of Photoelectrons – Phys. Lett. B 656, 25 (2007).

Cold trapped electrons are crucial for the antihydrogen experiments since we use these to cool antiprotons from keV energies down to the temperature of the trap apparatus. In our ATRAP-I apparatus we loaded these electrons from a field emission point. This loading method worked extremely well for precision measurements that required only small number of electrons. However, there were serious problems with this loading method when larger numbers of electrons had to be loaded repeatedly. For example, the cryogenic apparatus had to be frequently heated to room temperature to restore a significantly diminished electron accumulation rate.

As a replacement, we demonstrated that photoelectrons could be much more reliably accumulated in large numbers. Ten-nanosecond pulses of photoelectrons are liberated by intense UV laser pulses that strike a thin gold layer. The electrons are captured into a single-component plasma that is ideally suited to cool antiprotons for antihydrogen production. Up to a billion electrons are accumulated using a series of laser pulses (Fig. 5), more than are needed for efficient $\overline{\mathrm{p}}$ cooling in the large traps now being used for loading $\overline{\mathrm{p}}$ for $\overline{\mathrm{H}}$ production.

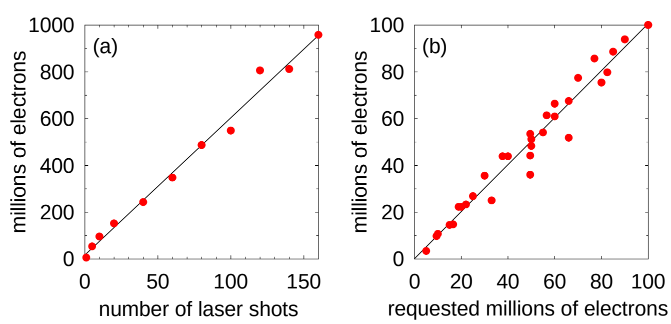

Figure 5: ((a) The number of photoelectrons in a deep trapping well increases linearly with the number of laser pulses. (b) A lower linear accumulation is made very insensitive to slow changes in laser intensity and alignment by lowering and raising the trapping potential to spill injected electrons above a certain number.

The method is demonstrated within a enclosed vacuum space that is entirely at 4 K, and is thus compatible with the exceptional cryogenic vacuum that is desirable for the long-term storage of antihydrogen. The pitfalls of other electron accumulation methods are entirely avoided, including the particle heating and declining efficiency of field emission point loading, and the heat load and contamination of thermionic emission methods. The method also works when instead the laser beam is directed through a small hole to strike the an electrode surface located upon the trap axis.

For the next grant period we will rely entirely upon the plasmas of photoelectrons for cooling antiprotons, and for capturing positrons transferred from the accumulator.

h. Magnetic Traps: Generations 1 and 2

A magnetic Ioffe trap intended to capture and store extremely cold antihydrogen atoms are now an important component of the research program, whose goal is the precise laser spectroscopy of trapped antihydrogen atoms. One model, conceptually design at Harvard and built by a German company in collaboration with our Juelich collaborators, is operating. It is a quadrupole Ioffe trap that can be turned on and off in minutes owing to its large inductance and the strong eddy currents induced in its metal housing and vacuum system. Fig. 6 shows scale drawings of the current carrying coils for the Ioffe trap that are outside of the Penning trap electrodes. We have learned a great deal from operating this trap about how to manage nearly 100 amperes of current within a cryogenic environment. The significant results that are the next two accomplishment items are carried out in this trap.

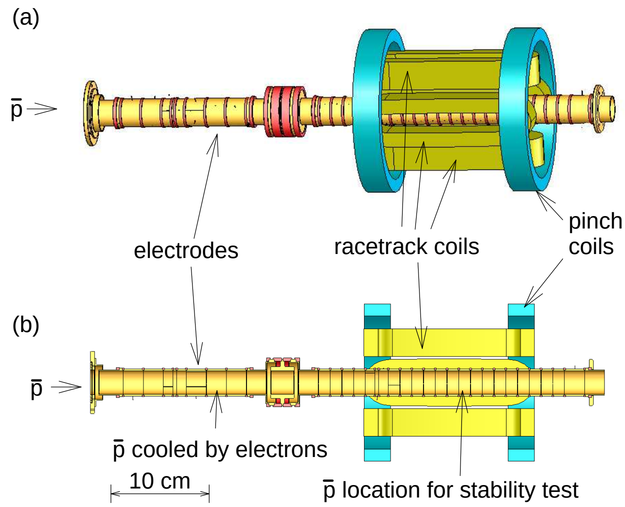

Figure 6: Outside (a) and cross section (b) views of cylindrical ring electrodes that are biased to form Penning traps for $\bar{p}$, e^+ and e^-. Along the symmetry axis of these electrodes is a 1-T bias field from an external solenoid (not shown). The axial and radial fields of a quadrupole Ioffe trap come from two pinch coils and four racetrack coils, respectively. Support structures, vacuum enclosures and helium dewars are not shown.

Based upon what we have learned, we designed a second generation magnetic trap, and this trap is now partly built by a company. This trap includes both a quadrupole and an octupole Ioffe trap. We expect that the former may be better for spectroscopy and that the latter may be better for initial particle capture, but this remains to be seen. This trap has a much lower inductance (and thus requires much more current to reach the same fields) and its support structure and vacuum housing is made entirely of epoxy fiber board rather than metal. The result is that we should be able to turn off the trap very rapidly, in less than 10 ms. We will thus be able to detect antihydrogen much more sensitively, by turning off the trap and detecting annihilation signals between background counts in the detector.

The company is making steady progress using a new manufacturing method whereby the superconducting wires are being embedded within epoxy fiber board layers. However, each week in our video conference with the folks who are doing the construction we learn not only about the week's progress but about why the schedule has slipped a bit. We still hope to have the new magnetic trap commissioned during our 2009 antiproton run, but unfortunately it seems increasingly likely that this will slip a year.

For the next grant period a big part of our effort will go into completing and commissioning the second generation Ioffe trap. This is a big undertaking insofar as new Penning traps (of much larger diameter and much more fragile), vacuum enclosures, helium dewars, cabling, high current leads, continuous flow helium replenishment, etc are involved. Plasma properties must be carefully controlled and measured, and a sensitive search for trapped antihydrogen atoms and the conditions that produce them will be carried out.

i. Charged Particles Successfully Stored Within a Penning-Ioffe Trap – Phys. Rev. Lett. 98, 113002 (2007).

One big success of the current grant period was to demonstrate that charged particles will remain trapped in the Penning traps when a Ioffe field is applied [8]. It was clear that a quadrupole Ioffe trap that could confine H atoms [9] for extremely precise laser spectroscopy [10] should confine similarly-cold $\overline{\mathrm{H}}$.

The threat was to the charged antiprotons and positons insofar as the Ioffe field dramatically destroys the axial symmetry and hence the angular momentum conservation that is the basis of a confinement theorem for the charged particles [11]. It is crucial that the charged antiprotons and positrons remain stored at least long enough to interact to form antihydrogen atoms if trapped $\overline{\mathrm{H}}$ atoms are the goal.

We were so concerned about this that we did a calculation based upon which we decided that it would be possible provided that the charged particle density was not too high, but we were not able to calculate the critical density [12]. Others picked up our concern and concluded that it would not be possible [13, 14]. We were concerned but not convinced.

In our initial demonstration we stored antiprotons and later electrons (as stand ins for positrons) in the center volume of the Ioffe trap, and then turned on the current for the Ioffe trap. The charged particles remained trapped for some minutes, long enough we thought to form antihydrogen atoms by either of the two production method that we had developed earlier – using a nested Penning trap [15, 16, 17, 18, 19] and using laser-controlled charge-exchange [20, 21]. .

j. First Production of Antihydrogen Within Penning-Ioffe Trap Fields – Phys. Rev. Lett. 100, 113001 (2008).

Another big success of the current grant period was to actually take the next step and demonstrate that antihydrogen could be produced with the Ioffe trap fields turned on [22]. Some new methods had to be devised to bring the antiprotons and positrons into contact in the presence of the diverging magnetic field lines. In this demonstration we actually observed that the number of detected $\overline{\mathrm{H}}$ atoms increases when a 400 mK Ioffe trap is turned on.

Crucial elements of the demonstration are short plasmas in a short nested Penning trap, a new method to keep e^+ and $\overline{p}$ interacting in a small volume, and coping with the slow cooling of the e^+ in a 1-T field. The $\overline{\mathrm{H}}$ form during the e^+ cooling of $\overline{p}$ in a nested Penning trap [15]. This is the most familiar of the two $\overline{\mathrm{H}}$ production methods that have been developed [23, 16] because it has produced most of the slow $\overline{\mathrm{H}}$ observed so far [18, 19, 17].

For the next grant period we greatly prefer to use the second generation Ioffe trap, when it is complete, because it will be so much more versatile. We must now go beyond the demonstration stage to optimize the $\overline{\mathrm{H}}$ production. We also intend to investigate for the first time the production of antihydrogen within a Penning-Ioffe trap via laser-controlled charge exchange [20, 21]. This seems promising but has not yet been tried.

k. Antihydrogen by Charge Exchange

Much larger plasmas of positrons are now available in the new ATRAP-II apparatus, so the number of antihydrogen atoms produced by the laser-controlled charge exchange method that we demonstrated earlier [21] should be significantly increased. We also developed a new diode-based green laser system and buildup cavity to better excite Cs atoms up to a Rydberg state, to replace the pulsed laser system used in the past. It is tunable and has a much narrower bandwidth. We also have incorporated a new and improved Cs source.

For the next grant period we thus hope to seriously investigate the laser-controlled charge exchange method with and without Ioffe fields applied.

l. Close to 1.1 K Positron Plasma Temperatures

We have designed and constructed a special pumped helium system to lower the temperature of our trap electrodes to 1.2 K. This is challenging given that the surrounding vacuum container for the trap electrodes is at 4.2 K (and up to 10 K in some apparatus versions). The new system seems to work very well, with 1.2 K electrode temperatures being measured at both ends of the very long stack of our cylindrical trap electrodes.

Electron and positron plasmas should cool efficiently by the spontaneous emission of synchrotron radiation until they are in thermal equilibrium with the surrounding trap electrodes. We believe that we may have produced 1.2 K electron and positron plasmas. However, some time will be required to demonstrate this clearly. Fig. 7 shows a preliminary, but very encouraging, indication that we have achieved this lowest ever plasma temperature with very large numbers of electrons.

The lower temperature is potentially extremely important. Our long term goal is to trap antihydrogen atoms. The depth of a good magnetic trap is only about a half Kelvin deep. Antihydrogen atoms that are made from plasmas that are 4 to 10 K by proven techniques cannot be colder than these temperatures. This

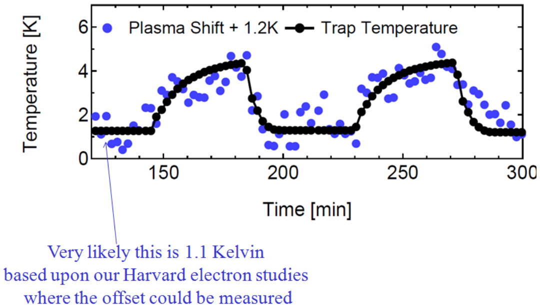

Figure 7: Preliminary indication of a 1.2 K electron plasma temperature.

means that very few of the produced antihydrogen atoms can possibly have an energy that is low enough for them to be trapped.

The situation changes dramatically going from 4 - 10 K down to 1 Kelvin. If a thermal distribution of antihydrogen atoms is produced, for example, the lower temperature goes into the exponent of a Boltzmann distribution for the energies of the antihydrogen atoms. The potential number of antihydrogen atoms cold enough to be trapped is thus much larger if this temperature is 1.1 Kelvin rather than 4 - 10 Kelvin.

For the next grant period we hope to clearly demonstrate the lower plasma temperatures, and then use the lower temperature plasmas to produced lower temperature antihydrogen atoms which can be trapped. We are also starting to look into using methods developed and demonstrated at Harvard to use a dilution refrigerator to lower the plasma temperature to 100 mK [24]. This difficult challenge will take not only a significant time to design, it will require significant equipment resources as well.

m. Observing Single Antiprotons Enroute to Searches for Antihydrogen Ions

We have long wished to see if either the antimatter counterpart of the negative hydrogen atom, or the antimatter counterpart of the hydrogen molecular ion, is produced when antiprotons and positron interact within a nested Penning trap. Extremely cold antihydrogen atoms could be created by cooling the charged molecules via collisions with laser cooled ions, and then photo-detaching the extra positron at threshold [25].

Long ago at LEAR we observed the production of negative hydrogen ions and used these to make what is still the best test of CPT invariance with a baryons/antibaryon system. In smaller traps than we currently use (not optimized for antihydrogen production) we were able to observe a single trapped antiproton and a single trapped negative hydrogen ion with great signal-to-noise. Since large numbers of antimatter ions are almost certainly not produced, a search for antimatter ions would required sensitivity to small numbers of ions – preferably only one. The first challenge of a search for antimatter ions is to see if we could achieve one-ion sensitivity in a larger trap designed for antihydrogen production.

We installed a first version of detection amplifiers designed to detect single and cool ions. These were used to detect and cool antiprotons. We were excited to eventually detect and distinguish individual antiprotons (Fig. 8) by resolving the cyclotron frequencies of antiprotons that were excited to very different cyclotron energies. We typically did these studies by keeping the last antiprotons that we captured in our trap at the end of a beam shift, and investigating these during following shifts while no additional antiprotons were available to us.

We encountered one unexpected challenge. When we ramped the Ioffe trap up and down during the shift we found a substantial change in the magnetic gradient; this changed our ability to resolve small numbers of ions. This requires more investigation, and the devising of methods to cope with or eliminate this complication.

For the next period we hope to improve our detectors and our method and make a serious search for antihydrogen molecules.

n. Continuous Source of Lyman Alpha Radiation

A continuous Lyman alpha laser system is needed for cooling trapped antihydrogen atoms and for initial spectroscopy experiments. The first continuous Lyman alpha system was demonstrated by ATRAP members several years ago [26].

Recent efforts have focused upon making a much more intense Lyman alpha source that is also much more robust, as is desirable for operation at an accelerator facility. A new solid state laser system has been constructed, and it recently produced its first Lyman alpha radiation. The first intensity was not high, and

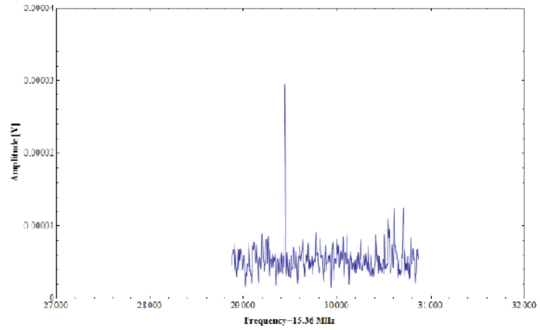

Figure 8: Observation of the radio signal from the cyclotron motion of a single antiproton. An antihydrogen ion should have about the same signal strength.

there has been some (recently remedied) trouble with a disk laser, but now that there is a signal to optimize considerable progress is expected.

For the next grant period our Mainz collaborators hope to increase the power of the continuous Lyman alpha system to as much as a 100 times higher than ever realized before. This should be enough laser power for laser cooling and for intial spectroscopy experiments on trapped antihydrogen atoms. Lyman alpha laser access to our trap is already available in our ATRAP apparatus. Our first generation Ioffe trap, and the second generation trap that is under construction, both have Lyman alpha access along and perpendicular to the trap axis. Before the solid-state Lyman alpha source arrives we hope to use diode lasers to develop and demonstrate the optics and alignment systems for directing the light through the trap when it is at cryogenic temperatures.

B. References

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